ESR line with decreasing temperature imply that the material might be metallic; if so, it might be an itinerant ferromagnet. Examples of the latter (such as $ZrZn_2$ and Ni_3Ga) show, qualitatively, features that are similar to the ones reported here (*31*).

$C_{60}(TDAE)_{0.86}$ is a "metallic" organic ferromagnet with a Curie temperature higher than any reported for other molecular ferromagnets based strictly on first-row elements. We note that the same basic molecule, namely C_{60}, supports ferromagnetism, metallic conductivity, and superconductivity (in the forms of K_3C_{60} and Rb_3C_{60}), a rather interesting and unusual occurrence.

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Early Differentiation of the Earth and the Problem of Mantle Siderophile Elements: A New Approach

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The long-standing problem of the excess abundances of siderophile elements in the mantle can be resolved by considering an equilibrium core-mantle differentiation in the earth at 3000 to 3500 kelvin. This high-temperature differentiation results in mantle siderophile element abundances that closely match the observed values. Some lithophile (light) elements could enter the core in this process as is necessary to account for its low density. The abundances of siderophile elements in the mantle are consistent with the conclusion derived from the recent physical models that the earth was molten during accretion.

RECENT PROGRESS IN THE DEVELopment of quantitative models of the accretion of planets has indicated that the earth was largely or totally molten during its accretion (*1*). For this initial state, the effect of pressure on melting in a planet of terrestrial size requires that a substantial amount of the planet would be at temperatures much higher than the low-pressure melting points of silicates and metallic iron. Differentiation to form an iron core and a silicate mantle would essentially be a high-temperature process, the temperature corresponding to the liquidus temperatures of iron and silicates at the prevailing pressures as the planet accretes. On the basis of a detailed investigation of the physical process of core separation in a largely molten earth, Stevenson (*2*) concluded that core segregation occurred rapidly under complete chemical equilibrium between the iron metal and mantle silicates. In such a case, the abundances of siderophile elements in the mantle would be controlled by distribution coefficients (K_d's) applicable to the temperatures and pressures at which the core-mantle equilibrium was established and not by the K_d's at the relatively low temperatures measured in the laboratory. This point has not been considered so far in the use of abundances of siderophile elements in the mantle as constraints to theories of the early chemical differentiation of the earth [for example (*3, 4*)].

In this report, I examine a model of core formation in which the siderophile element partitioning between the core and the mantle occurred at temperatures close to the liquidus temperatures in the accreting earth. Other than the consideration of the effect of temperature, all assumptions remain the same as in earlier discussions, namely, that the partitioning of trace components between two phases occurs at equilibrium and that the phases relevant to core-mantle differentiation in the earth are dominantly Fe-metal and liquid silicates.

The temperatures at which core-mantle equilibrium in the earth was established cannot be specified exactly. Most modern theories of accretion suggest that the earth would be molten by the time it had grown to about one-tenth of its present mass (*1, 5, 6*). Core formation will commence at this stage and continue through the stochastic accretion process by the infall of 10^{25}- to 10^{26}-gram planetary embryos (*1*). Thus we can expect that successive fractions of the core separate from the mantle silicates at their liquidus temperatures in this growing proto-earth. Because the interior pressure in the planet in the initial stages of accretion would be less than that in the present earth, the silicates and metal would have melted at temperatures lower than those at depth in the present earth. On the basis of data on melting of mantle silicates as a function of pressure, it can be inferred that core formation commenced at about 2500 K when the earth is about one-tenth of its present mass. As accretion continued, the sinking Fe-metal droplets would have equilibrated with mantle silicates at progressively higher temperatures because of the increase in the melting points of mantle silicates in response to the increased pressure in the interior. In the final stage of accretion when the earth

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had nearly attained its present mass, the temperature of equilibration before a metal droplet settled into the core would have been close to the melting point of mantle silicate Mg-perovskite at the core-mantle boundary, at about 4500 K (7). Thus, during the accretion of the earth, the core material equilibrated with mantle silicates at temperatures in the range of 2500 to 4500 K. The relative proportions of the core material that segregated under the low- and high-pressure regimes during accretion cannot be estimated in any quantitative fashion. In the following discussion, I consider a core-mantle equlibration in the range of 3000 to 3500 K.

The effect of temperature on distribution coefficients can be evaluated by considering the simple physical model of a solute distributed between two solvent liquids. For a component ι distributed between two liquid phases α and β at equilibrium, the chemical potentials of the component ι in the two phases are equal; thus $\mu_{\iota\alpha} = \mu_{\iota\beta}$. If we assume that Henry's Law is obeyed,

$$\mu^0_{\iota\alpha} + RT\ln\chi_{\iota\alpha} = \mu^0_{\iota\beta} + RT\ln\chi_{\iota\beta}$$

where $\chi_{\iota\alpha}$ and $\chi_{\iota\beta}$ are the equilibrium concentrations of ι in the phases of α and β, μ^0 represents the chemical potential of the pure component in a hypothetical standard state in which the component at unit concentration has the properties that it would have at infinite dilution, R is the gas constant, and T is temperature. Because $(\chi_{\iota\beta}/\chi_{\iota\alpha})$ is the distribution coefficient K_d, the above equation can be rearranged to yield the relation $K_d = \exp(\Delta\mu^0/RT)$, where $\Delta\mu^0 = (\mu^0_{\iota\alpha} - \mu^0_{\iota\beta})$. By definition, for a given component and composition of phases α and β, $\Delta\mu^0$ is a constant at the standard state temperature and pressure. If the effect of pressure is ignored, laboratory measurements of K_d at a given temperature can be used to determine $\Delta\mu^0$ and K_d at some other temperature (Table 1). As can be seen from Table 1, the K_d's for the moderate to strongly siderophile elements at high temperatures are up to several orders of magnitude less than the values at the temperature of the laboratory measurements.

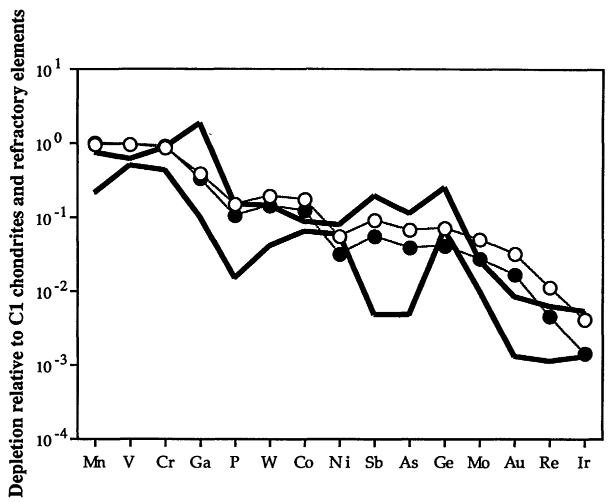

Fig. 2. The observed mantle depletions (bold lines, Fig. 1) and calculated depletions of siderophile elements for core-mantle equilibrium separation at 3000 K (solid circles) and 3500 K (open circles). The error limits due to the uncertainties in the measured distribution coefficients used to obtain calculated values are not shown but are of the order of a factor of 2 to 5 for the strongly siderophile elements.

The above discussion of the effect of temperature on distribution coefficients is unduly simplified in that it assumes ideality (Henry's Law) and has neglected to consider the effect of pressure, which is known to be important in the earth (8). For the first assumption, there is some support from experimental work for some of the trace elements that I have considered (9, 10). It is not known at present if the pressure effects are in the same direction as the temperature effects, although simple thermodynamic considerations are suggestive of this. Equally unknown is the magnitude of the pressure effect. Keeping in mind these important caveats, I present a heuristic exercise in exploring the early differentiation history of the earth below.

The abundance patterns of siderophile elements in the mantle relative to C1 chondrites have been discussed in several recent papers (3, 11, 12). Newsom (11) evaluated the mantle abundances of some critical siderophile elements after making corrections for the enrichment of refractory lithophile elements in the earth relative to C1 chondrites and losses due to volatility. Although there are large uncertainties for some elements, the general abundance pattern of siderophile elements in the mantle, shown by the bold solid lines in Fig. 1, seems well enough established to be useful in constraining the early differentiation history of the earth. The observed pattern has the following characteristics: the least siderophile elements Mn, V, Cr, and Ga are at or slightly below chondritic abundances; the moderately siderophile elements P, W, Co, Ni, Sb, As, Ge, and Mo are depleted to levels of ~0.1 to 0.02 of chondritic abundances; and the highly siderophile elements Au, Re, and Ir are depleted to ~0.01 to 0.001 of chondritic values. Another important feature of the mantle siderophile abundances is the near chondritic ratios of some elements with widely differing K_d's, for example Co/Ni, Au/Ir, and Re/Ir (3, 4). These characteristics of the mantle siderophile elements have been interpreted to preclude core-mantle differentiation at equilibrium (13) and as evidence against an initially molten earth (3, 4). A cornerstone of these arguments is a comparison of the observed abundances of siderophile elements in the mantle to the abundances predicted by the use of K_d's determined in the laboratory, an approach advanced nearly 25 years ago by Ringwood (15). For the latest available data on the mantle siderophile abundances (11), if the laboratory K_d's in Table 1 are used, the fit is acceptable for the least siderophile elements, but a large number of moderate to strongly siderophile elements in the mantle appear to be in excess of the expected values by several orders of magnitude (Fig. 1). In addition,

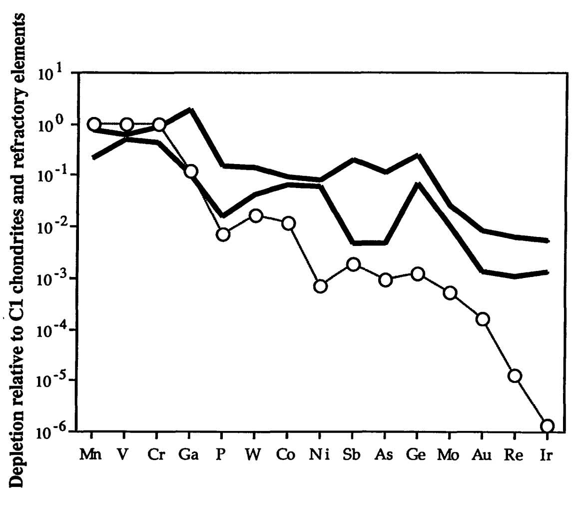

Fig. 1. Depletion of some siderophile elements in the mantle relative to C1 chondrite, and corrected for refractory element enrichment in the earth and for losses due to volatility for Mn, Cr, Ga, P, Sb, As, and Ge (8). The upper and lower limits of observed mantle abundances (bold lines) represent the observed low and corrected high values of mantle abundances from (11). Open circles show calculated abundances for an equilibrium core-mantle separation at 1600 K.

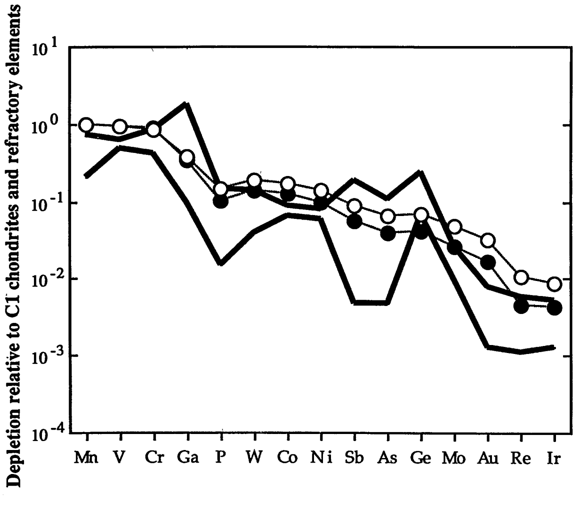

Fig. 3. The observed mantle depletions (bold lines, Fig. 1) and calculated depletions of siderophile elements as in Fig. 2, for a model in which core separation occurs from a molten mantle with 5% of solid silicates followed by 30% olivine fractionation into the upper mantle. The Co/Ni, Au/Ir, and Re/Ir ratios are in the range of observed values in the mantle.

the pattern does not meet the requirement of near chondritic ratios such as Co/Ni, Au/Ir, and Re/Ir observed in the mantle.

Efforts to account for the apparent excess siderophile abundances and the near chondritic ratios of the elements mentioned above have led to the exploration of many complex models of earth accretion and differentiation. These include models ranging from disequilibrium core-mantle segregation (*13*), equilibrium models in which the core contains significant amounts of other elements (*14, 15*), inefficient core formation in which some Fe-metal and sulfides are left behind in the mantle to be subsequently oxidized (*16*), heterogeneous planetary accretion models with multiple stages of accretion (*17*), and models in which giant impacts provide late-stage accretionary components (*18*). As discussed in recent reviews (*11, 12*), all of these proposals encounter some difficulties; the most successful are the ones with the most adjustable parameters.

I consider below a simple model in which the core-mantle differentiation occurs under equilibrium conditions at high temperatures in a molten earth during accretion. I used the high-temperature K_d's in Table 1 to derive an expected pattern of siderophile element abundances in the mantle for Fe-metal core models at 3000 and 3500 K (Fig. 2). In contrast to the poor match between the calculated and observed abundances for the 1600 K equilibration (Fig. 1), the use of high-temperature K_d's brings the calculated and observed abundances of the moderate to strongly siderophile elements into agreement. However, the high-temperature models fail to achieve the near chondritic Co/Ni, Au/Ir, and Re/Ir ratios, as in the observed mantle.

These near chondritic ratios seem to be unique to the earth and are not observed in other planetary bodies, such as the moon, the eucrite parent body, and the shergottite parent body (Mars?) for which data are available. I suggest two possible explanations, one or both of which might have operated in the earth. The first is the proposal of Agee and Walker (*19*) that during crystallization of the mantle after core formation, about 30% olivine was fractionated into the upper mantle. This feature may have occurred on the earth, but not the moon or Mars because of the pressure-density relations required for olivine flotation. This process will have the effect of enriching Ni and Ir relative to Co and Au in the upper mantle. The effect of such an addition of olivine to the upper mantle can be estimated from the available olivine-melt K_d's for these elements. The second possibility is that core segregation occurred in a molten mantle containing a small percentage of solid silicates. In such a case, the equilibrium distribution of a siderophile trace element occurs between the metal, liquid silicates, and the solid silicates. This effectively changes the metal-silicate bulk K_d's. The observed Co/Ni ratio in the mantle is 1.1. The calculated mantle Co/Ni ratios after core separation from a molten mantle with 5% solid silicates are from 3.1 to 2.4 in the 3000 and 3500 K differentiation models. For the olivine-melt K_d's given in (*4*), a 30% olivine addition to the upper mantle produces a Co/Ni ratio of 1.5 in the 3000 K model and 1.4 in the 3500 K models, in approximate agreement with the observed value. The observed mantle Au/Ir ratio is not as precisely known as the Co/Ni ratio; the permissible range of values is between 1 and 6 (*11*). After core separation, the calculated value are 3.4 in the 3500 K model and 2.3 in the 3500 K model. The fractionation of olivine as above will produce a mantle Au/Ir ratio of 2.7 in the 3500 K model and 1.9 in the 4000 K model, which are within the range of the observed value. Finally, the Re/Ir ratios are near unity in both the 3000 K and 3500 K models. Thus, the combined effect of a core-mantle differentiation at near liquidus-temperature of the mantle silicates and subsequent olivine fractionation into the upper mantle seems to provide a close match to the observed abundances of siderophile elements in the mantle and the near chondritic elemental ratios of some siderophile elements (Fig. 3).

The so-called "excess siderophile elements" in the mantle may thus simply be an artifact of the use of low-temperature K_d's to deduce the consequences of high-temperature differentiation in the earth. A differentiation of the core and mantle in a molten earth during accretion eliminates the long-standing paradox of the excess siderophile elements and satisfactorily accounts for the abundances of siderophile elements in the mantle in a simple and straightforward manner.

There are other consequences of the model

Table 1. Measured distribution coefficients at 1573 K used in this work are calculated for an oxygen fugacity of 12.5 from the references cited. The high-temperature distribution coefficients are calculated as described in the text.

Element	K_d 1573 K	K_d 3000 K	K_d 3500 K	Reference
Mn	0.0023	0.1165	0.153	(*9*)
V	0.0095	0.1165	0.153	(*9*)
Cr	0.078	0.31	0.356	(*9*)
Ga	16	1.7	1.6	(*10, 23*)
P	300*	12.9	9.4	(*23, 28*)
W	130	8.63	6.6	(*23*)
Co	175	9.85	7.4	(*23*)
Ni	3,000	33.9	21.8	(*23, 25*)
Sb	1,100	22.2	15.1	(*24, 26*)
As	2,300	30.8	20.1	(*24, 26*)
Ge	1,700	20.6	14.1	(*23*)
Mo	4,000	19.4	13.4	(*23, 27*)
Au	13,000	66.4	39.3	(*27, 28*)
Re	166,000	207	106	(*16, 29*)
Ir	1,660,000	574	260	(*16*)

*The distribution coefficient is multiplied by 10 to take into consideration the unusual behavior of this element with respect solid and liquid Fe-metal (*29*).

of early differentiation of the earth proposed here. Core-mantle differentiation at high temperatures provides a direct mechanism for the incorporation of some highly lithophile elements into the core. Metal-silicate partitioning data for such elements are not available. However, if the dominant lithophile elements in the mantle, Mg, Si, and O, have low-temperature (1500 to 1600 K) metal-silicate K_d's in the range of 10^{-4} to 10^{-6}, as would be consistent with their strongly lithophile nature, core-mantle differentiation at 3000 to 3500 K could have resulted in the incorporation of ~1 to 3% of each of these elements into the core, in addition to S which will enter the core as Fe-S melt (*20*). Thus, a high-temperature differentiation of the earth is consistent with the low density of the core.

The presence of radioactive heat sources in the core has been a much debated topic (*21, 22*). High-temperature differentiation may also lead to the incorporation of significant amounts of radioactive elements into the core. Distribution coefficients for U and Th have not been measured, but the K_d for K of about 10^{-2} (*22*) indicates that ~10% of the earth's inventory of K could be partitioned into the core, in which case it would provide an important energy source in the core. Precise measurements of metal-silicate distribution coefficients for the lithophile and radioactive elements are needed to verify these suggestions of light elements and radioactive energy sources in the core.

In summary, consideration of the effect of temperature on K_d's indicates that the abundances of siderophile elements in the mantle can be satisfactorily accounted for by core-mantle differentiation at high temperatures during the accretional history of the earth. The low density of the core may be a result of this process. This scenario of the early chemical differentiation of the earth is entirely consistent with recent physical models of planetary accretion that postulate that the earth was largely or totally molten during accretion. It appears that the siderophile element abundances in the mantles of terrestrial planets may be useful as geothermometers of initial planetary differentiation.

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A Mechanical Trigger for the Trot-Gallop Transition in Horses

Claire T. Farley and C. Richard Taylor

It is widely thought that animals switch gaits at speeds that minimize energetic cost. Horses naturally switched from a trot to a gallop at a speed where galloping required more energy than trotting, and thus, the gait transition actually increased the energetic cost of running. However, by galloping at this speed, the peak forces on the muscles, tendons, and bones, and presumably the chance of injury, are reduced. When the horses carried weights, they switched from a trot to a gallop at a lower speed but at the same critical level of force. These findings suggest that the trot-gallop transition is triggered when musculoskeletal forces reach a critical level.

Quadrupeds walk at low speeds, trot at moderate speeds, and gallop at high speeds. Within each gait, they prefer to use a narrow range of speeds where the energetic cost of moving each kilogram of their body mass a meter (cost of transport) is minimizes (*1*). An earlier study from our laboratory showed that at these preferred speeds, horses naturally use the gait that minimizes energetic cost (*1*). It seems reasonable that horses switch from one gait to another at the speeds that minimize energetic cost (*1–3*). However, the earlier study did not include systematic measurements of the gait transition speeds (*1*). It is difficult to imagine how energetic cost could trigger a gait transition as an animal rapidly changes speed. In terms of the available biological transducers, it seems more likely that musculoskeletal forces trigger the transition from trotting to galloping. In dogs, goats, and horses, peak skeletal forces increase with trotting speed and are reduced when they switch to a gallop (*4–7*). By galloping rather than trotting at higher speeds, the peak forces and presumably the chance of injury are reduced. Although even higher forces occur during jumping or falling than during locomotion (*7*), these are rare events. A horse's feet hit the ground

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